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14. ABSTRACT

This report discusses recent progress in understanding turbulent, lifted hydrocarbon jet flames and the conditions under which they stabilize, which has implications for both gaseous- and spray-burner design. Experiments are discussed which support the importance of a variety of effects, including partial premixing, local extinction, streamline divergence, air co-flow and and large-scale structures. Specifically, advances in flame hystersis and propagation are reported, which have helped clarify the overall understanding of combustion in jets.

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Final Report on Flame Stabilization and Structure of Reaction Zones

ABSTRACT

This report discusses recent progress in understanding turbulent, lifted hydrocarbon jet flames and the conditions under which they stabilize, which has implications for both gaseous- and spray-burner design. Experiments are discussed which support the importance of a variety of effects, including partial premixing, local extinction, streamline divergence, air co-flow and and large-scale structures. Specifically, advances in flame hystersis and propagation are reported, which have helped clarify the overall understanding of combustion in jets.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

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"Turbulent Lifted Flames in the Hysteresis Regime and the Effects of Co-flow" S. D. Terry and K. M. Lyons, ASME Journal of Energy Resources Technology 28 (4): 319-324 (2006).

"Toward an Understanding of the Stabilization Mechanisms of Lifted Turbulent Jet Flames: Experiments" K. M. Lyons, Progress in Energy and Combustion Science. 33 (2): 211-231 (2007).

"Upstream Islands of Flame in Lifted-Jet Partially-Premixed Combustion", K. M. Lyons, K. A. Watson C. D. Carter and J. M. Donbar, Combustion Science and Technology 179 (3) 1029-1037 (2007). .

"Observations on Upstream Flame Propagation in the Ignition of Hydrocarbon Jets" J. L. McCraw, N. J. Moore and K. M. Lyons; Flow Turbulence and Combustion 70 (1) 83-97 (2007).

"Effects of dilution and co-flow on the stability of lifted non-premixed biogas-like flames" D. A. Wilson and K. M. Lyons: Fuel. Volume: 87Issue: 3 Pages: 405-413 (2008).

"Observations on Jet Flame Blowout" N. J. Moore , J. L. McCraw and K. M. Lyons; International Journal of Reacting Systems. In Press.

"On Flame-Edge Propagation" K. M. Lyons, J. L. McCraw , N. J. Moore, K. A. Watson, C. D. Carter and J. M. Donbar Flow Turbulence and Combustion, 80 (3) 405-410 (2008).

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"Turbulent Lifted Flames near Blow-Out Conditions in Air Co-flows" J. L. McCraw, , N. J. Moore, and K. M. Lyons, Fire and Materials 2007 INTERFLAM 2007 (Sept), London.

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"Observations on Upstream Flame Propagation in Ignited Hydrocarbon Jets" J. McCraw, N.J. Moore and K. M. Lyons, Western States of the Combustion Institute, Spring Meeting, Boise Idaho, March 2006.

"Observations on Lifted-Flame Oscillations and Flame Stability Near Blowout" N. J. Moore, and K. M. Lyons, Joint States Meeting of the Combustion Institute, Spring Meeting, San Diego, March 2007.

"Flame Hysteresis Effects in Methane Jet Flames in Co-Flow" N. J. Moore, K. M. Lyons and S. D. Terry, Joint States Meeting of the Combustion Institute, Spring Meeting, San Diego, March 2007.

"Effects of the Leading-Edge Reaction Zone on Lifted Flame Oscillations", N. J. Moore and K. M. Lyons, Eastern States Combustion Meeting Oct 2007.

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(d) Manuscripts

"On Diluted-Fuel Combustion Issues for Burning Biogases" D. A. Wilson and K. M. Lyons: In Review: ASME Journal of Energy Resources Technology.

"Leading-Edge Flame Oscillations in Lifted Turbulent Flames" N. J. Moore and K. M. Lyons, In Review: Combustion Science and Technology.

"Leading-Edge Velocities and Lifted Methane Jet Flame Stability" W. Wang and K. M. Lyons In Review: Combustion Science and Technology.

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Graduate Students	
NAME	PERCENT_SUPPORTED
Nancy Moore	0.50
Jennifer McCraw	0.25
David Wilson	0.25
Steve Terry	
FTE Equivalent:	**1.00**
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Names of Post Doctorates

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FTE Equivalent:	
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NAME	PERCENT_SUPPORTED	National Academy Member
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NAME	PERCENT_SUPPORTED
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Names of Personnel receiving masters degrees

NAME
David Wilson
Jennifer McCraw
Total Number: **2**

Names of personnel receiving PHDs

NAME
Stephen Terry
Total Number: **1**

Names of other research staff

NAME	PERCENT_SUPPORTED
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Problem Studied: Elements of reaction zones and oscillations that will appear in both gaseous and spray flames

Introduction

The mechanisms that govern flame stability can be studied in a system like a lifted turbulent jet flame burning in the presence of co-flowing air. By increasing the fuel or co-flow velocity, an attached flame will lift off the nozzle and stabilize at a mean lifted height, with a tendency to oscillate axially about that mean position. In numerous industrial applications such

as furnaces and burners, the location of the flame base and thus the location of the maximum heat release is an important design element. Flow velocities beyond a critical value result in the flame moving to a region downstream in which the fuel concentration is generally low, and blowout occurs, resulting in the loss of unburned fuel and lower efficiency.

Recent theories on the stability mechanism of lifted flames stem from the premixed model of Vanquickenborne and van Tiggelen (1966), the flamelet extinction model of Peters (1984, 2000), and the large scale mixing model of Broadwell (1984). Vanquickenborne and van Tiggelen (1966) proposed that the fuel and oxidizer are completely premixed at the lifted flame base and subsequently the flame stabilizes where the stoichiometric mixture is formed. An equilibrium results between the premixed turbulent burning velocity and the flow velocity. The theory of Broadwell (1984) challenges the premixedness model by proposing that lifted flame stabilization depends on the turbulent structures of the nearby unignited flow. Fresh ambient air is reentrained into the diffusion flame and comes into contact with a mixture of hot products and fuel. Molecular diffusion occurs at the strained interface until the entire mixture is homogeneous. The flamelet extinction model of Peters (2000) suggests that the stability of the lifted flame is governed by the strain rates within laminar diffusion flamelets. At certain jet exit velocities, the high strain rates from turbulent eddies cause extinction of the flamelets near the nozzle resulting in the flame stabilizing at a lifted height downstream.

Numerous studies have investigated the effect of fuel exit conditions on the lift-off height of methane flames both computationally (Muller *et al.*, 1994, Montgomery *et al.*, 1998, Kumar *et al.*, 2007) and experimentally. The increase in liftoff height with increasing jet exit velocity has been observed in many experiments (Muñiz and Mungal, 1997, Brown *et al.*, 1999, Lee *et al.*, 1997, Kalghatgi, 1984). Results of cinema-PIV (particle image velocimetry) experiments on

lifted flames performed by Upatnieks *et al.* (2004) suggest that at low Reynolds numbers, edge flame extinction plays the central role in flame stabilization. The turbulence level and the laminar flame propagation speed were not found to be strongly linked. PIV experiments by Schefer and Goix (1998) at higher Reynolds numbers show that the flow velocities at the stabilization point are below the turbulent flame propagation speed which challenges the theory of Vanquickenborne and van Tiggelen (1966).

Areas downstream such as the end of the potential core region and the far-field are typically defined as functions of the nozzle diameter. The jet development region is considered to be in the range of 4 to 5 nozzle diameters downstream, and the fully-developed region is beyond 12 diameters (Cessou *et al.*, 2004). Similarity solutions for the jet velocity are valid beyond 20 diameters downstream (Wygnanski and Fiedler, 2006). Kalghatgi (1984) found that the height of a lifted flame is independent of the nozzle diameter in the far-field (approximately 20 diameters). Results from Terry and Lyons (2006) and Cessou *et al.* (2004) show that the heights of turbulent flames (particularly in the near-field) are conditional on the nozzle diameter, with a larger nozzle resulting in lower positions.

An essential aspect to understanding flame stabilization is the characterization of the magnitude of the axial oscillations of lifted flame reaction zones (Hammer, 1993). Despite being globally stable, the lifted flame is observed to propagate upstream and recess downstream aperiodically (Hammer and Roshko, 2000). The fluctuations have been observed as increasing with increasing height (Muñiz and Mungal, 1997). Kelman *et al.* (1998) investigated this phenomenon with laser imaging of the temperature and concentrations at the flame base. They conclude from their research that oscillations result from upstream premixed flame propagation with large-scale fluid structures producing downstream movement. Also, Watson *et al.* (2000)

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found that CH-PLIF leading-edge structures facilitated the propagation into the unburned fuel-air mixture. This connection between height oscillations and large structures in the flow field is consistent with the work of other researchers (Muñiz and Mungal, 1997, Miake-Lye and Hammer, 1988, Chao *et al.*, 2002).

The current paper discusses an experimental study of the oscillations of a lifted methane-air jet reaction zone with various co-flow velocities. The reaction zone liftoff-height oscillations are studied to shed light on the stabilization mechanisms that prevent flames from receding downstream and extinguishing. Rather than focus on detailed instantaneous images of reaction zones, the current work has utilized time sequences of the reaction zone to determine temporal oscillatory behavior. Various combinations of fuel and co-flow velocities with Reynolds numbers from approximately 3000 to 10,000 are used to study lifted flames at a wide range of downstream locations for two different nozzle diameters. Details of the flame position and the change in height with time are provided and interpretations of the data are discussed.

Experimental Setup

The experiments were performed at the Applied Energy Research Laboratory on the campus of North Carolina State University. The jet flame burner consisted of a fuel nozzle that is concentric with a pipe of 150 millimeter (mm) diameter through which co-flowing air is released (Figure 1). The air co-flow velocity was measured with a TSI Veloci-calc model 8345 anemometer. For this experiment, fuel tubes of 3.5 mm and 5.0 mm inner diameter, with lengths sufficient to create fully-developed turbulent flow, were used to deliver 99% pure methane to the

jet. An Advanced Specialty Gas Equipment rotameter (tube FM4336) was employed to measure the fuel jet exit velocity.

Images of the oscillating flame were made with a Panasonic Model PV-GS300 CCD video camera producing thirty frames per second and were post-processed. Figure 1 contains two illustrations depicting lifted flames at different moments in time. For each, the instantaneous flame height, h', is herein defined to be the axial distance from the nozzle exit to the flame base, which is the furthest point upstream at which flame luminosity is detected by the camera.

Results and Discussion

Numerous cases were studied to determine characteristics of oscillations with respect to downstream location and flow velocities. Data were obtained from video imaging of the flames subsequent to the flame reaching steady-state behavior. Previous research has found that flame height oscillations are not periodic (Hammer and Roshko, 2000); thus this work focused on thirty-second intervals which were deemed adequate to capture the representative oscillations and include the trends of the flame movement.

Figure 2 shows the temporal position of the flame for five different fuel exit velocities with no co-flow present and a nozzle diameter, d, of 3.5 mm. The instantaneous flame height was measured from the video image once per a time step of approximately 0.167 seconds. This data was used to produce the trace of the flame at each fuel velocity shown in the figure. The oscillations of the flame in each case are clear from the peaks and valleys in the traces, but for the time interval studied, no periodic behavior is evident. Similar data acquired for all of the cases with both nozzle diameters confirms the irregularity.

For each fuel tube, five different fuel exit velocities were used for each of three predetermined co-flow velocities. The range of co-flow and fuel velocities chosen allowed for numerous cases to exist as turbulent lifted flames beyond the hysteresis region (Terry and Lyons, 2006). The instantaneous height from each video image was used to determine the average height for each flow velocity combination. Table 1 provides the data for each case studied and the calculated average lifted-height. The compilation of data shows that for a given co-flow velocity, the height increases as the fuel velocity increases. In addition, the presence of co-flow tends to move the lifted height further downstream. If one compares two flames from the small nozzle for 22.6 m/s fuel velocity, the average height with no co-flow present is 3.12 cm, yet with 0.52 m/s co-flow velocity it is 10.09 cm. Similarly, for the large nozzle and a 24.3 m/s fuel velocity, the height increases from 4.21 cm to 16.82 cm with the addition of 0.64 m/s co-flow velocity. This underscores the profound impact of even a small co-flow velocity (Muñiz and Mungal, 1997).

The effect of the flow on the lifted height is evident in Figures 3(a) and (b) which plot the change in average height due to jet exit velocity, U_0, for each co-flow velocity, U_{cf}, and nozzle diameter. As the fuel velocity increases, the average height generally increases, for a given co-flow. For the same approximate U_0, the presence of co-flow moves the stable height downstream. The height change with U_0 per co-flow velocity is linear for the majority of cases, with some exceptions at the upper and lower limits (an observation also noted in Cessou *et al.* (2004)). Also shown in Figures 3(a) and (b) are the maximum oscillation amplitudes observed for each case, designated by vertical bars, both upstream and downstream of the average height. Although the amplitude of oscillations increases with downstream location, the presence of co-flow reduces the amplitude for a given average lifted height. Furthermore, the maximum

oscillation amplitude during downstream recession is seen to be equal to or greater than the maximum during upstream propagation with few exceptions.

Histograms of the normalized height fluctuations for each case per co-flow velocity serve to illuminate the likelihood of the flame at any given instant of time existing near the average height. Figure 4 contains data for the small nozzle with no co-flow velocity (the same data used in Figure 2). The graph shows the percentage of occurrences that each h'/d value fell within each bin and the normalized average height for each case (marked with an X along the horizontal axis). Thus for the case with 22.6 m/s fuel velocity, h'/d was within the bin containing the normalized average height (about 8.9) approximately 12% of the sampled data. For the largest percentage of occurrences (20%), h'/d was within the next bin downstream. As the fuel velocity increases, the oscillation amplitudes increase and the maximum bin percentage decreases; however, the average height is within or close to the most frequented bin. For 49.6 m/s fuel velocity, the maximum percentage is only 10%, which is the bin containing the normalized average. The distribution for each case is close to being symmetric which agrees with findings reported in Cessou *et al.* (2004) for flames stabilized in medium and high velocity domains.

Knowing the extent to which turbulence influences flame height and oscillations is vital to understanding the mechanisms controlling flame location. All of the cases reported in this study are in turbulent flow regimes, with the Reynolds numbers based on exit conditions ranging from around 2800 to 10,700. Figure 5 shows that the normalized average heights increase with increasing Reynolds number though the large nozzle data produces lines with a smaller slope. Also, for comparable co-flow velocities, h/d is less when the large nozzle is used. From the figure, a normalized height of 20 cm can be achieved by flows with Reynolds numbers anywhere

between 3000 and 10,000. These results suggest that viscous dissipation does not play a primary

role in determining the downstream location at which a flame stabilizes.

Generally, as seen in Figure 5, the lifted height of a flame at a particular Reynolds

number is not consistent. Thus, an effective jet velocity utilizing the density ratio helps to better

relate the lifted height to flow velocities. As Montgomery *et al.* (1998) and Kumar *et al.* (2007)

discussed, the effective jet velocity is calculated using a relation from Kalghatgi (1982) as:

$$U_{eff} = U_0 + C\sqrt{\rho_{cf}\Big/\rho_0}\, U_{cf}$$

in which U_{eff}, U_0, and U_{cf} are the effective, fuel, and co-flow velocities, respectively, and ρ_{cf}/ρ_0

is the ratio of the co-flow to fuel densities. The constant C is chosen such that the data collapses

to a linear relation. When $C = 40$ (the value also used in Kumar *et al.* (2007)), the height data

from both size nozzles collapses and allows for the prediction of the flame lifted height, as

shown in Figure 6.

The height fluctuations, h', are normalized by the average height, h, and plotted against

h/d in Figure 7. For each case, the maximum oscillation amplitude downstream is marked with a

solid symbol and the maximum upstream is marked with the outline of the same symbol.

Usually, the flame recessed further downstream than it propagated upstream, but this was not

always observed. For flames stabilized at *h < 10d*, the fluctuations were generally above *0.3h*.

Downstream of this region where the turbulence can be assumed to be fully developed, the

oscillation behavior was more uniform with data showing *h' ≤ 0.3h*. Approaching blowout (*h >*

35d) the fluctuations were not significantly greater except for the case with no co-flow present.

However, results published by Hammer and Roshko (2000) of height fluctuations for several

fuels at high Reynolds numbers showed that when normalized by height, the height fluctuations increased with height and as blowout was approached. Also, they found that the ratio h'/h did not significantly change with nozzle diameter, a finding supported by the current work.

Rate of oscillations

Using the heights from images taken during the thirty seconds of flame burning, the change in height with respect to time was examined. This oscillatory rate, dh'/dt, uses a lab frame of reference and is positive for downstream recession. Because the radial flame position was not noted with the height, dh'/dt has only an axial component. The root mean square of dh'/dt (found with a backward differencing algorithm) was plotted with the Reynolds number for both nozzles to establish the relationship between the oscillatory rate and the amount of turbulence (Figures 8(a) and (b)). The data from the small nozzle shows a sharp increase in dh'/dt above $Re = 8500$; this trend is not seen as plainly in the large nozzle data. Upatnieks *et al.* (2004) used cinema-PIV to study turbulent flames and found that the propagation of the flame base was close to the laminar flame speed. They surmised that streamline divergence at the flame front and not turbulence intensity is the primary factor in lifted height for conditions in which $Re < 8500$. Also, the propagation speed was not clearly linked to the passage of large eddies. Thus, the data of Upatnieks *et al.* (2004) and of the current study support the concept of edge-flames more strongly than turbulent flame propagation theories that are more likely relevant at $Re > 8500$.

While the normalized amplitude of oscillations appears to be independent of downstream location except in the areas near the nozzle and approaching blowout (as seen in Figure 7), the oscillatory rate is somewhat correlated with height. Figure 9 shows that the oscillatory rate

increases as the normalized average height increases. However, at a given height, *dh'/dt* is less when co-flow is present; suggesting that the presence of co-flow has a greater affect on the oscillatory rate throughout the entire flowfield than it does on the normalized amplitude.

The effective velocity can once again be applied to collapse the data into a linear relation useful for predicting the oscillatory rate for given fuel and co-flow velocities. Figures 10(a) and (b) show the root mean square of *dh'/dt* plotted with U_{eff} for the small and large nozzles, respectively. The small nozzle data correlated with the equation for U_{eff} when $C = 5.2$ (the value used in Montgomery *et al.* (1998)). For the large nozzle data, $C = 15$ provided the best agreement. Montgomery *et al.* (1998) speculated that the constant, C, in the effective velocity equation takes into account chemical kinetics and burner characteristics. However, the oscillatory rate data does not collapse for the same value used previously with the normalized average height data (see Figure 6). Moreover, data from each nozzle requires a different C value for optimal agreement.

Oscillations preceding blowout

At high flow velocities, a flame can be unable to sustain combustion and blows out. The blowout phenomenon has been regionalized to separate the pulsating behavior of the flame, similar to the oscillations of stable flames, from the onset of receding that leads to blowout. However, instability of the flame in the pulsating region means that oscillations are not always observed before blow out occurs (Chao *et al.*, 2000). A previous study by the authors of this paper observed flames for which the jet velocity was set high enough to cause the flame to blow out for three different co-flow velocities and a nozzle diameter of 3.5 mm (Moore *et al.*, 2008). The average height during oscillations within the pulsating region, defined to be bounded by the

first and the last upstream propagation seen in the motion of the flame, was found to be more than $50d$ for each case.

Figures 11(a) and (b) allow direct comparison of the stable flames discussed previously (specifically in Figures 8(a) and 9) and the three flames in the process of blowing out. The oscillatory rates for the blowout cases are plotted versus the Reynolds number in Figure 11(a). While it is not necessary for the Reynolds number to be exceptionally high for blowout to occur, the oscillatory rates of the flames preceding blowout are about four times higher than their stable flame counterparts. In addition, the blowout flames show a change in behavior at $Re = 8500$ similar to that seen in the stable flames. The relationship between the average heights and the oscillatory rates shown in Figure 11(b) indicates that a general trend is true for both stable and unstable flames; the height is proportional to the oscillatory rate, with a sharper increase in height occurring at low rates.

Summary of Most Important Results

Results from analysis of stable lifted turbulent methane-air flames in this study are intended to give a comprehensive view of flame height oscillations in terms of fuel and co-flow exit velocities. The following conclusions have been drawn about the average height, the oscillation amplitude, and the oscillatory rate:

1. The average height of each stable flame increases with flow velocity. The flame must recess downstream to a location where it can propagate against the incoming flow. The flame height is affected by the presence of co-flow but not by the amount of turbulence. For a given Reynolds number the flame can exist at multiple locations.

2. The oscillation amplitude for a flame stabilized further downstream is greater than one stabilized closer to the nozzle. The presence of co-flow does not stop a lifted flame from oscillating but limits the amplitude (when compared to a flame at a similar height without co-flow). The normalized height fluctuations show little variation with height except at locations close to the nozzle or approaching blowout far downstream.

3. The oscillatory rate increases with Reynolds number though a change in the relationship is seen at $Re > 8500$. The rate is much higher for flames preceding blowout despite the Reynolds numbers being comparable. An increase in height also causes an increase in the rate, a trend that holds for unstable flames preceding blowout.

The ambiguous relationship between these three oscillation characteristics is further supported by plots of the height and the oscillatory rate with the effective velocity. To best linearize the data, different values of the constant coefficient, C, must be used which leads to doubts about the characteristics dictating the coefficient's value. Also, the change in nozzle diameter requires a different C for the oscillatory rate but not for the height, suggesting that burner characteristics have more of an effect on oscillatory rate. The results imply that while the largest scales of turbulence may influence the lifted height, viscous dissipation plays a primary role in the oscillation behavior.

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Figure Captions:

Figure 1. Two examples of a lifted methane flame. The fuel is delivered from the nozzle that is surrounded by co-flowing air. h' is the instantaneous axial distance from the fuel nozzle to the lifted flame base.

Figure 2. Height fluctuations during a 30 second interval for five fuel velocities with no co-flow present, 3.5 mm nozzle diameter. The behavior is not periodic for any of the cases.

Figure 3. Average height for each set of flow velocities for the (a) small nozzle and (b) large nozzle. The vertical bars indicate the greatest oscillation amplitudes observed both upstream and downstream.

Figure 4. Histogram of height oscillations for 5 cases with no co-flow present, 3.5 mm nozzle diameter. Each X marks the average height for each case.

Figure 5. Average height normalized by the nozzle diameter for each set of flow velocities. The smaller nozzle data is indicated by solid lines and the larger nozzle data by dashed lines.

Figure 6. Normalized height plotted with the effective velocity, $C = 40$. The smaller nozzle data is indicated by solid lines and the larger nozzle data by dashed lines.

Figure 7. Height fluctuations normalized by the average height for each case. Because oscillation fluctuations are not generally symmetric about the average height, the greatest downstream h' (marked by a solid symbol) and the greatest upstream h' (marked by a symbol outline) for each case are shown.

Figure 8. RMS of dh'/dt for the (a) small nozzle and (b) large nozzle.

Figure 9. Change of *dh'/dt* with stable normalized height.

Figure 10. RMS of *dh'/dt* for the (a) small nozzle and (b) large nozzle. Each nozzle diameter requires a different value of *C* to linearize the data when plotted versus U_{eff}.

Figure 11. Comparison of stable and unstable flames. (a) RMS of *dh'/dt* for the small nozzle with three cases of blowout included. (b) Effect of height on *dh'/dt*.

Table Captions:

Table 1. Fuel velocities used for each nozzle diameter and co-flow velocity. The average height for each case is also provided.

Lifted Flame

Nonreacting region

h_1

h_2

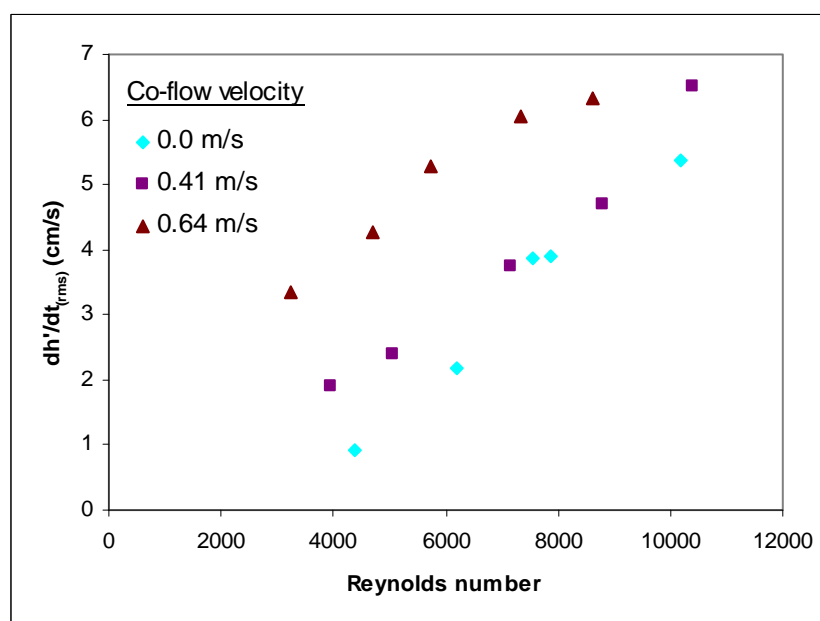Co-flow Air

Methane

Methane

Co-flow Air
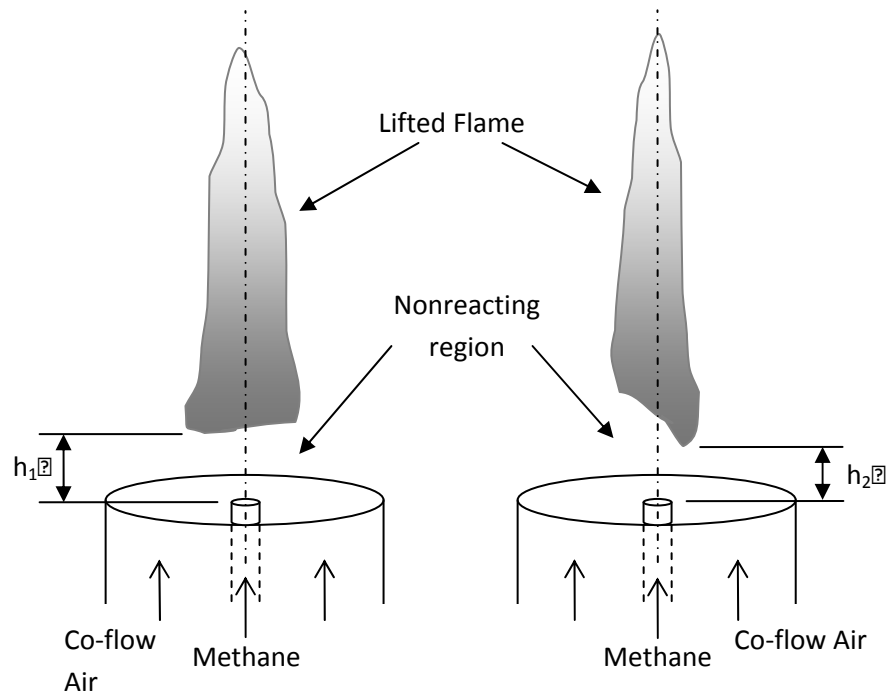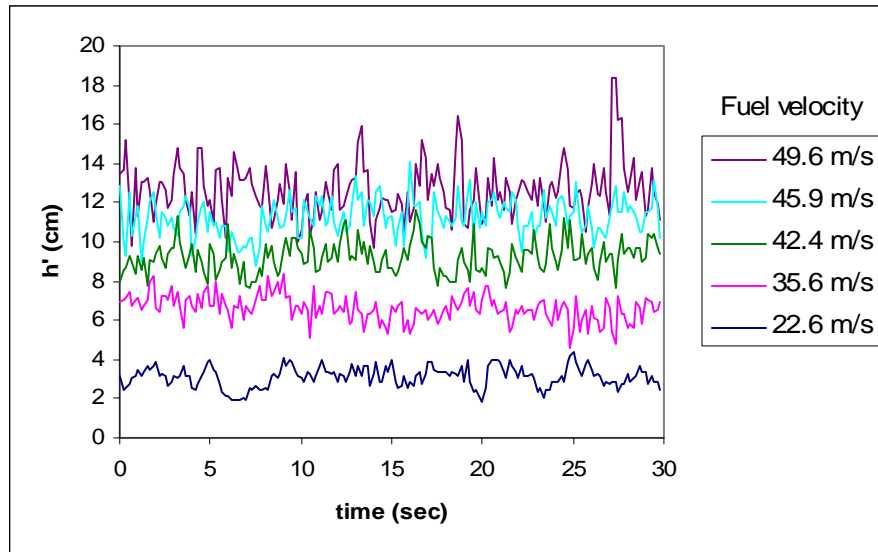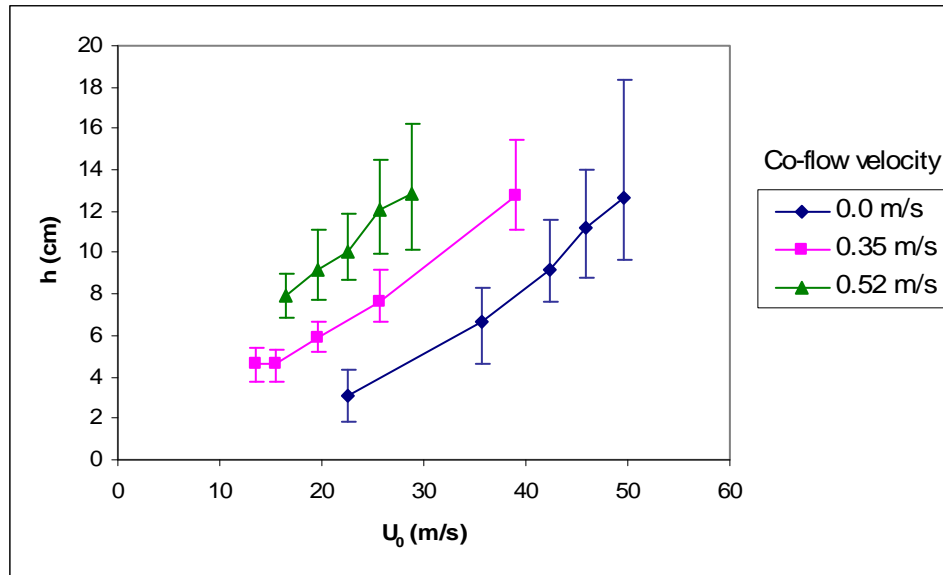
Figure 1.

Figure 2.

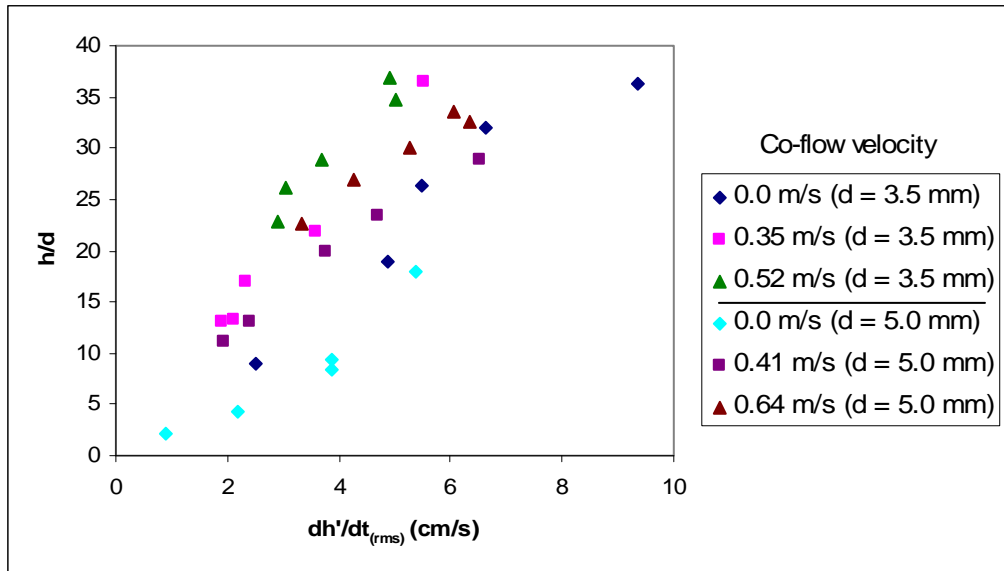(a) 3.5 mm nozzle diameter
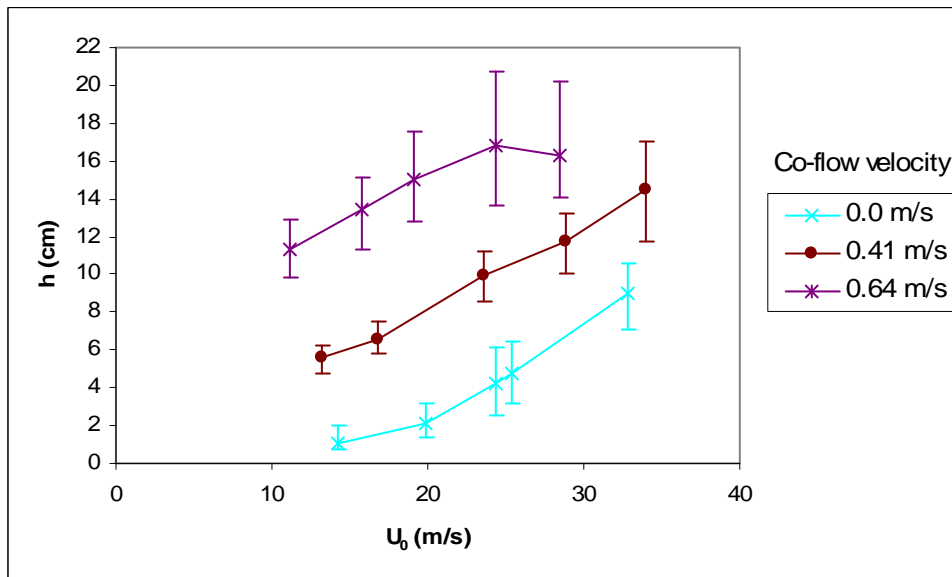
(b) 5.0 mm nozzle diameter

Figure 3.
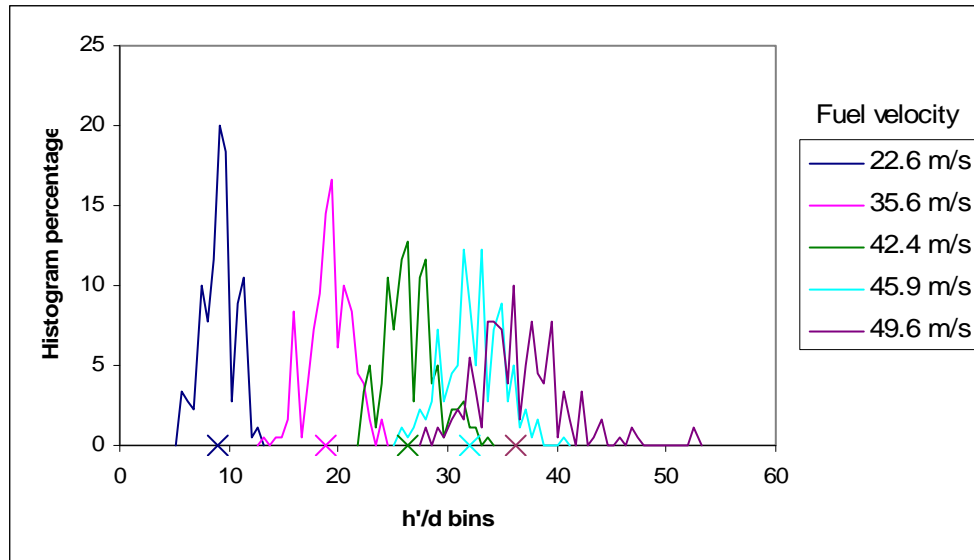
Figure 4.
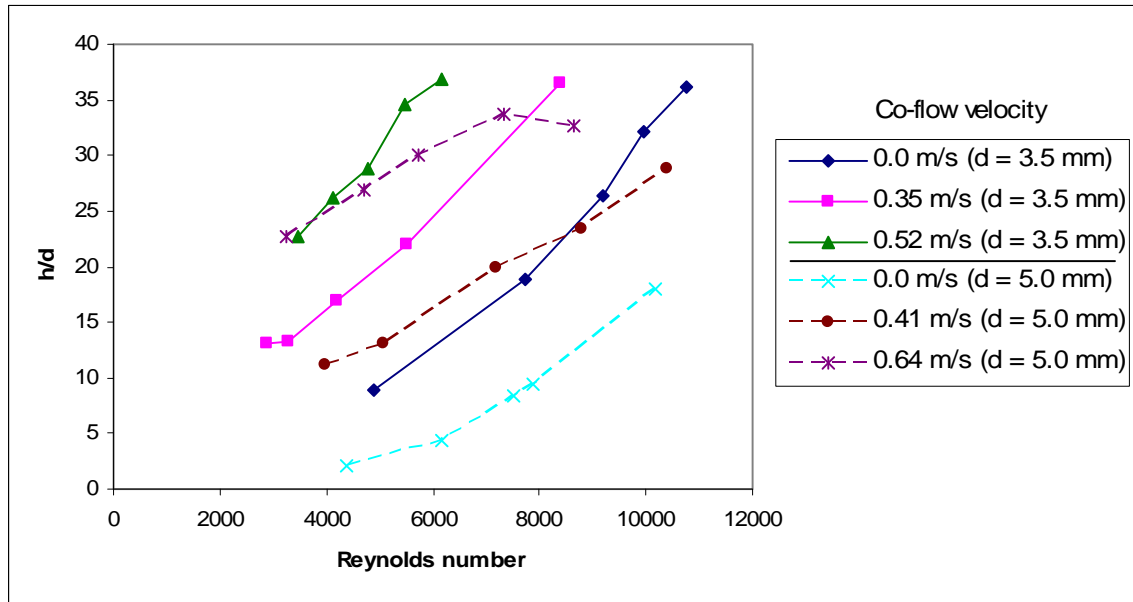
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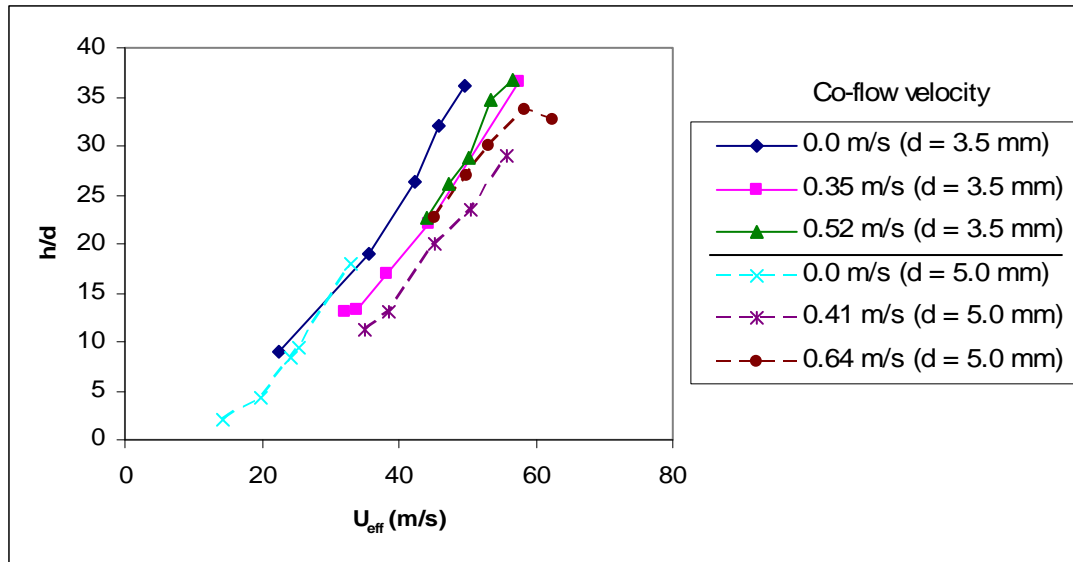
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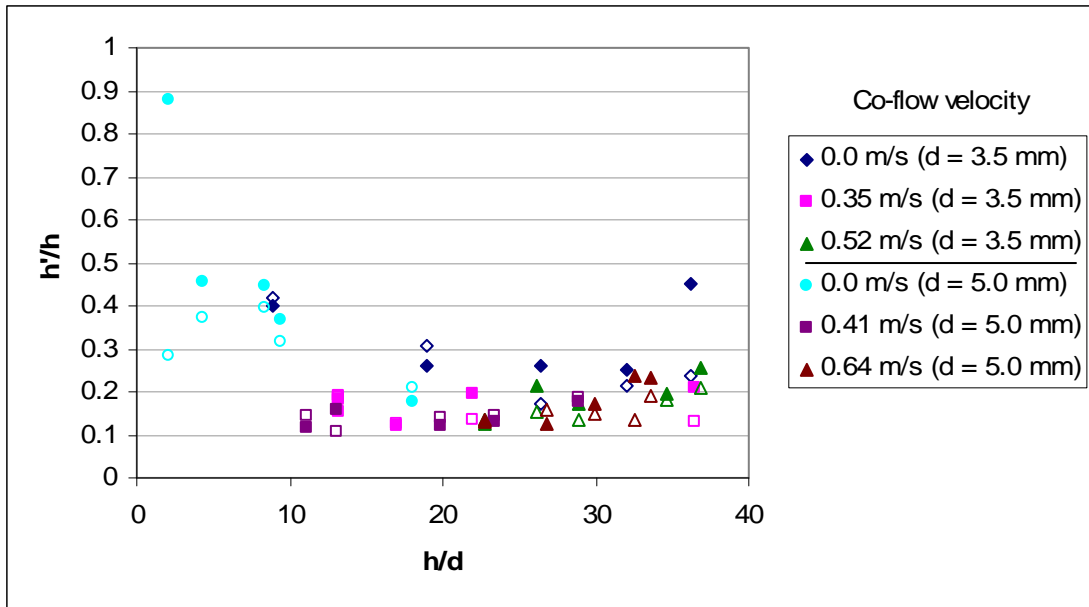
Figure 7.
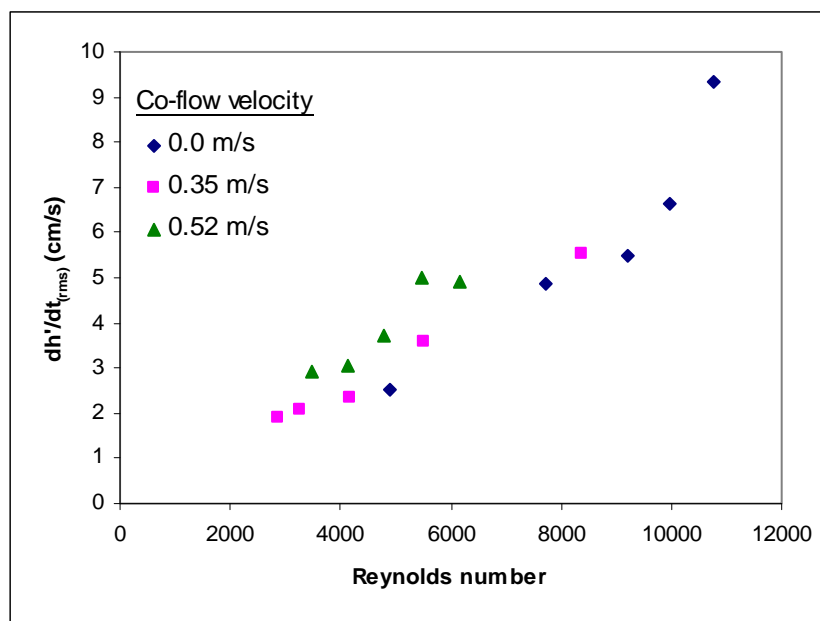
(a) 3.5 mm nozzle diameter

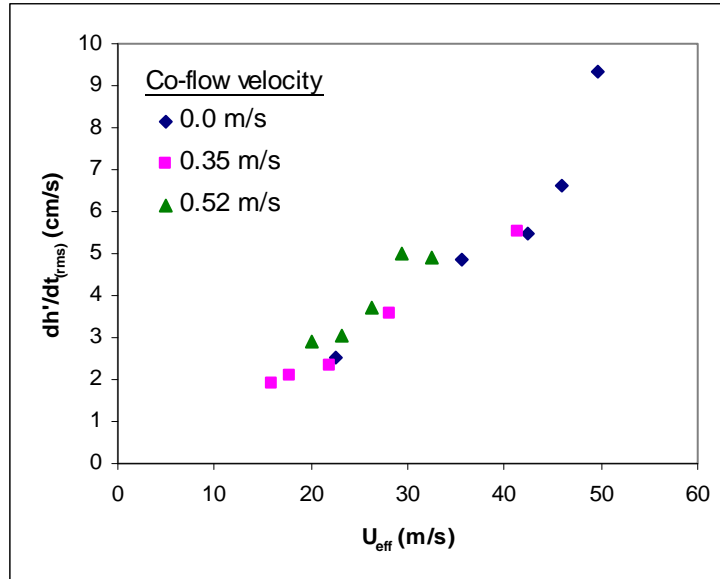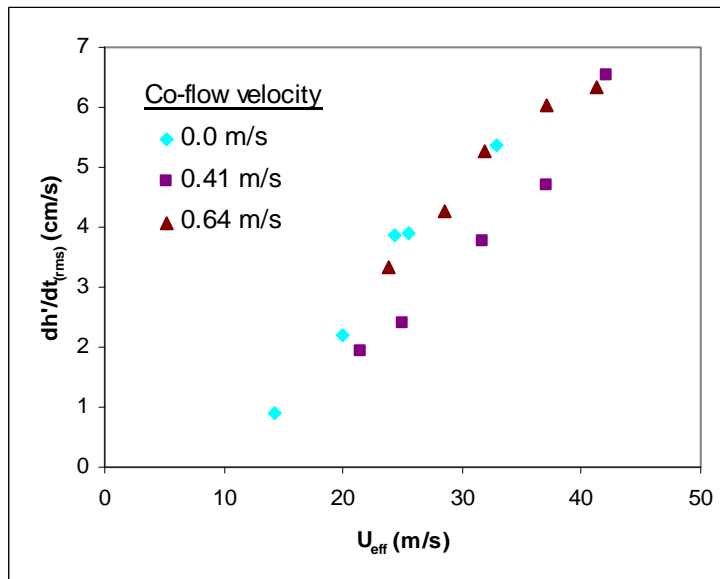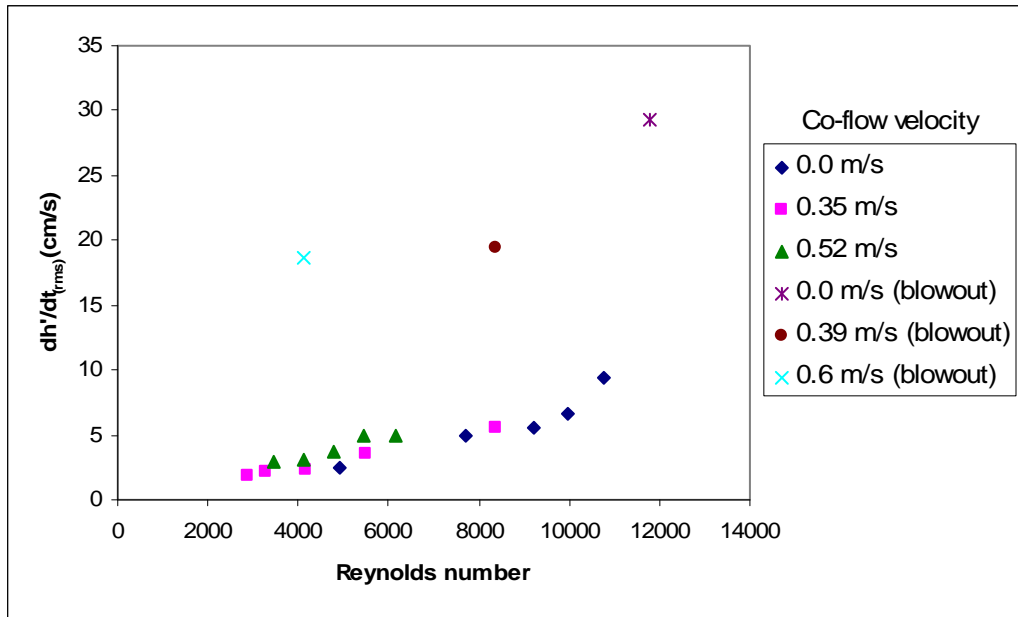(b) 5.0 mm nozzle diameter

Figure 8.

Figure 9.

(a) small nozzle with $C = 5.2$

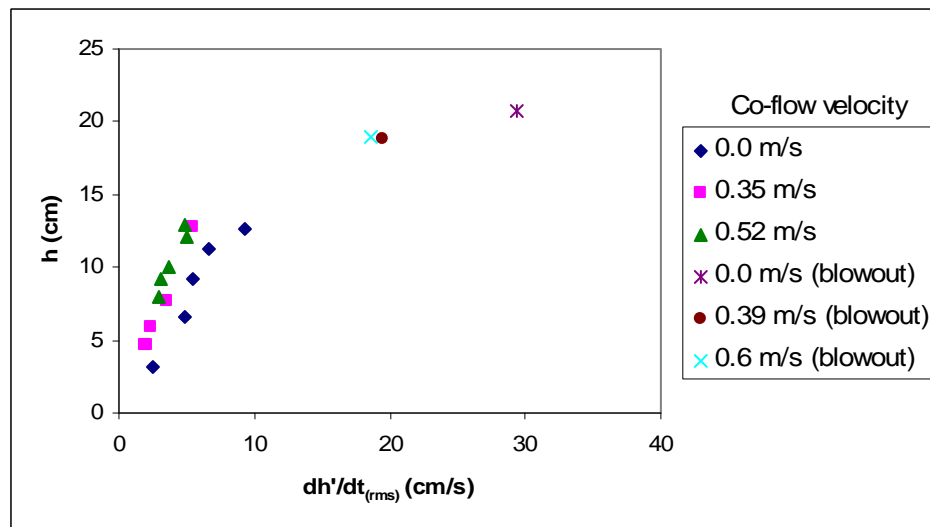
(b) large nozzle with $C = 15$

Figure 10.

(a)

(b)

Figure 11.

Nozzle diameter, d = 3.5 mm

Co-flow velocity, U_{cf} = 0.0 m/s					
Fuel velocity, U_0 (m/s)	22.6	35.6	42.4	45.9	49.6
Average height, h (cm)	3.12	6.62	9.22	11.23	12.67
Co-flow velocity, U_{cf} = 0.35 m/s					
Fuel velocity, U_0 (m/s)	13.6	15.4	19.6	25.7	39.0
Average height, h (cm)	4.60	4.64	5.93	7.68	12.77
Co-flow velocity, U_{cf} = 0.52 m/s					
Fuel velocity, U_0 (m/s)	16.5	19.6	22.6	25.7	28.9
Average height, h (cm)	7.96	9.15	10.09	12.12	12.89

Nozzle diameter, d = 5.0 mm

Co-flow velocity, U_{cf} = 0.0 m/s					
Fuel velocity, U_0 (m/s)	14.2	19.9	24.3	25.4	32.9
Average height, h (cm)	1.05	2.15	4.21	4.71	9.00
Co-flow velocity, U_{cf} = 0.41 m/s					
Fuel velocity, U_0 (m/s)	13.2	16.8	23.6	28.8	33.9
Average height, h (cm)	5.58	6.51	9.95	11.71	14.45
Co-flow velocity, U_{cf} = 0.64 m/s					
Fuel velocity, U_0 (m/s)	11.1	15.8	19.1	24.3	28.5
Average height, h (cm)	11.36	13.42	14.99	16.82	16.31

Table 1.